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CERTIFICATE

This certificate is issued in support of an application for Patent registration in a country outside New Zealand pursuant to the Patents Act 1953 and the Regulations thereunder.

I hereby certify that annexed is a true copy of the Provisional Specification as filed on 4 October 2002 with an application for Letters Patent number 521823 made by INDUSTRIAL RESEARCH LIMITED.

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Dated 6 November 2003.

Neville Harris

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Commissioner of Patents, Trade Marks and Designs

COMMISSIONER OF PATENTS, TRADEMARKS & DESIGNS
NEW ZEALAND

Patents Form No. 4 Our Ref: CC503786

Patents Act 1953

PROVISIONAL SPECIFICATION

ANTENNA ARRAY

We, **INDUSTRIAL RESEARCH LIMITED,** a New Zealand company, of Brooke House, 24 Balfour Road, Parnell, Auckland, New Zealand do hereby declare this invention to be described in the following statement:

PT0438986

Antenna Array

Technical Field

The present invention relates to electromagnetic antennas and in particular, but not exclusively, to microwave antennas suitable for a microwave sensor for use in the detection of material characteristics of objects.

Background

Industrial sensing has been evolving and there has been an increasing interest in development of new sensor solutions. One of the problems that has been solved by using microwave sensing techniques is the inspection of the material properties in the interior of a dielectric object. This can be achieved by measuring the interaction of an electromagnetic wave with an object under test, either by measuring its complex permittivity, or by measuring the scattering of the radiated wave from the object.

Most of the techniques for permittivity measurements are destructive, requiring the sample to be cut and fitted into the measurement device. Examples are the use of a resonant cavity and a waveguide cell for permittivity measurement. However, in such cases, the sample preparation is not only time consuming, but also inappropriate for many practical applications, particularly the inspection of natural products. A specific example is the inspection of apples, where the goal is to detect the apples with a water core (rotten). This can be easily detected by means of a resonant cavity microwave sensor, since the water in the damaged apples significantly increases the measured permittivity. However, it is clear that cutting every apple is a poor solution.

There are other techniques for permittivity measurement, which do not require sample preparation, where sensors such as a coaxial probe and an open waveguide flange are used. However, these techniques require good contact between the sensor and the measured object. Very often this is undesirable, for example in the food processing industry, where cleaning the probe may need to be performed after every measurement to meet health requirements. Furthermore, the contact between the probe and the measured object presents a problem for objects with curved or irregularly shaped surfaces, as the required uniform pressure of the probe onto the surface cannot easily be achieved.

As a solution to these problems, the interaction of the radiated field with the material under test may measured. This measurement setup is used for non-destructive and non-contact sensing.

Using such a system, it is possible to measure the permittivity of the material under test or, as is often needed in practice, to perform an inspection of a product's quality by comparing measured attenuations through both perfect and damaged samples. Horn antennas may be used to transmit and receive the microwave energy and the transmission coefficient, or attenuation in dB, is measured.

However, when dielectric objects such as natural products are measured, small discontinuities only introduce a small change in attenuation, for example of the order of 0.1 dB. It is difficult to detect such small changes using horn antennas, partucularly when the scattering from the surrounding object is of the same order of magnitude, making these measurements inconclusive in most cases.

In such applications, it may be advantageous to have a measurement system with a focused beam, in which the electromagnetic enery is converging towards the object under test (OUT). When the OUT is positioned in the beam waist (focus), all the energy is confined to pass through it, which significantly improves the sensitivity of the measurement system and the measured change in attenuation can be several dB. The advantage of the focused beam system is its capability to filter out reflections from adjacent objects. The measurement errors due to specular and diffuse reflections from the adjacent objects are minimised in this system.

Focused-beam systems have been developed that focus a horn antenna's diverging beam, with a dielectric lens as a focusing device. In such a system, most of the energy is transferred from one feed horn to the other, without significant losses and reflection interference from surrounding objects.

This system suffers from several disadvantages. First, the size of the system is usually very large, since the dielectric lens design should have dimensions covering several wavelengths in order to prevent waves diffracted from the lens edges interfering with the measurement. Even if the lens is mounted on the mouth of the horn, the size of the horn itself is significant and not practical for many applications.

A beamforming microstrip constrained lens (MCL) is described in the specification of United States Patent No. 4,721,966. The term 'constrained' is used to characterise the class of microwave lenses defined as any optical transforming device in which the rays

are guided and constrained to follow discrete paths that may have different propagation characteristics. The MCL includes a number of guiding elements to receive microwave energy from a horn antenna and the path lengths and the geometries of these guiding elements, which constitute the lens, are designed so that the exit rays produce the desired phase and amplitude distributions across the aperture.

The application of either a MCL or a dielectric lens in focused beam systems has a number of disadvantages. The problems that occur with these systems are: defocusing with a change of frequency, diffraction of the direct wave from the lens edges and its intereference with the focused beam, high attenuation of the electromagnetic wave by the lens material, the size of the measurement system, high fabrication costs and expensive lens material. In addition to these problems, MCL systems have a significant problem with spurious radiation from transmission lines and coupling slots.

It is thus an object of the present invention to provide a focussing electromagnetic antenna that overcomes or alleviates at least some of the problems in focussing anetannas at present, or at least to provide the public with a useful alternative.

Further objects of the present invention may become apparent from the following description.

Summary of the Invention

According to one aspect of the invention, there is provided a focussed beam antenna array including a plurality of element antennas and a feeding network connecting said element antennas and one or more microwave sources and providing a feeding coefficient for each element antenna, wherein either one or both of:

i) the relative position of the element antennas, and

ii) the feeding coefficient for each element antenna

are selected to cause microwave signals transmitted from the antenna array to focus on a required focal surface.

Preferably, the relative position of the element antennas and/or the feeding coefficient for each element antenna is selected to position the beam waist in a predetermined position in a transversal plane relative to the direction of propagation of said microwave signals.

Preferably, the required focal surface is at a predetermined focal distance within the near field zone from the element antennas.

Preferably, said feeding network includes a power divider or network of power dividers between said one or more sources and said element antennas, so that each element antenna is fed with microwave signals of substantially equal amplitude.

Preferably, the element antennas are located relative to each other in a preselected configuration, the configuration selected to assist the focussing of said electromagnetic signals transmitted from said element antennas.

Preferably, the element antennas are located at a separation of approximately one wavelength of the transmitted microwave signals from each other.

Preferably, the feeding coefficient for each element antenna is determined to cause a phase variation in signals received by the element antennas that is substantially equivalent to the phase variation that would occur in signals transmitted through a portion of a dielectric thin lens having the same radial distance as the element antenna.

Preferably, the feeding network may include contolled electronic phase shifters controlled by control means to allow variation of the location of the focal surface.

Preferably, the antenna array includes no lenses.

According to another aspect of the present invention there is provided a method of producing a focussed beam antenna array, the method including providing one or more element antennas for receiving microwave signals from a microwave source and transmitting microwave signals, wherein the method includes one or both of:

i) locating the element antennas at certain locations relative to each other; and

ii) selecting a certain feeding coefficient for each element antenna

in order to achieve a phase variation in microwave signals across the antenna array that causes the antenna array to have a predetermined focal surface at a required distance from said element antennas.

Preferably, the method includes selecting the feeding coeffcients for each element antenna to position the beam waist in a required position in a transversal plane relative to the direction of propagation of said microwave signals.

Preferably, the method includes locating the element antennas with varying separation in a plane transverse to a direction of transmission of the antenna array in order to achieve a focussing effect.

Preferably, the method includes locating the element antennas at different locations along the axis of transmission of the antenna array in order to achieve a focussing effect.

Preferably, the focal surface is located within the near field zone of said antenna array.

Preferably, the method may include selecting the feeding coefficient for each element antenna so that the antenna array simulates a dielectric thin film lens.

Preferably, the method may include either or both of changing the electrical length of transmission lines to each antenna alement and using phase shifters to set the feeding coefficient for each element antenna.

Further aspects of the present invention, which should be considered in all its novel aspects may become apparent from the following description, given by way of example only and with reference to the accompanying drawings.

Brief Description of the Drawings

<u>Figure 1</u>: shows a schematic representation of an antenna array in accordance with an aspect of the present invention.

<u>Figure 2</u>: shows a diagramatic representation of a transformation of microwave signals from a diverging beam to a converging beam.

<u>Figure 3</u>: shows a top view of an antenna array in accordance with an aspect of the present invention, showing one possible positioning of element antennas.

<u>Figure 4</u>: shows a bottom view of the antenna array of Figure 3 showing a feeding network of transmission lines for the element antennas.

Modes for Performing the Invention

The present invention provides an antenna solution with a converging beam. The antenna solution may have particular application to the focussing of electromagnetic signals and may be particularly suited to focussing signals in the near field zone.

Figure 1 shows a diagrammatic representation of an antenna array 100 in accordance with the present invention. The antenna array 100 includes a substrate 10 on which is located a number of element antennas 1a-1j, each of which are fed by a corresponding transmission line 2a-f. Each transmission line 2a-f provides a feeding coefficient

indicated by $a_1 - a_j$ for its respective element antenna 1a-f and is fed from a microwave signal source (not shown). The feeding coefficient for an element antenna is the amplitude and phase of that element antenna with respect to a reference element. Throughout this specification, locations are indicated with reference to the coordinate system x, y, z as shown in Figures 1 and 2 and r is the radial distance in the x,y plane from the centre of the antenna array 100 (see Figure 2).

Adjustment of the phase of electromagnetic signals can be achieved by adjusting the feed coefficients a_1 to a_j, for the elements of the antenna array provided on the z = z' plane. With particular reference to Figure 2, to calculate the required feeding coefficients, a thin dielectric lens may be observed. The choice of the lens geometry by which the focusing effect is achieved is arbitrary. The description herein is given with particular reference to an embodiment of the invention using a spherical lens as a reference. However, those skilled in the relevant arts will appreciate after reading this specification that other lens contours, for example a hyperbolic contour, may be used.

The lens surface is discretised into equal sized cells 3. When fabricating the antenna array 100 every elemental cell 3 contains an element antenna 1 for the array counterpart of the lens. In order to transform the diverging wavefront U(x,y) into a converging wavefront U'(x,y), generally, or transform a plane wave into a spherical converging wave, by analogy with thin lenses, an element antenna 1 at the radius r from the lens centre should have a phase of the feeding coefficient defined by equation 1.

$$\phi(r) = \frac{\pi r^2}{\lambda f} \qquad \text{... equation 1}$$

In equation 1 λ is a wavelength and f is the required focal point distance.

Therefore, if the incoming wave U(x,y) is a plane wave U(x,y)=E=1, then the field distribution after the lens is equal to E', as shown in equation 2.

$$E' = \exp\left(j\frac{2\pi}{\lambda}n\Delta_0\right)\exp\left(-j\frac{\pi r^2}{\lambda f}\right) \qquad \text{... equation 2}$$

In equation 2 n is the index of refraction and Δ_0 is the thickness of the lens for $y = 0$.

Therefore, the phase of the feeding coefficient 2 for an element antenna is calculated from the position of the element antenna 1 and comparing it with the ray in the dielectric lens at the same position. Thus, the focusing effect is achieved by controlling the relative

phase difference between the element antennas feeding coefficients 2. All element antennas 1 in the array will typically have equal feeding amplitude. The focal surface need not be planar, although in many situations it is anticipated that a planar focal surface would be preferable.

Physical displacement of the element antennas 1 may be used in order to achieve a required phase distribution. This is a feature that can also achieve the focusing effect and provides an additional degree of freedom, which can be used together with or independently from the electrical line length variation to achieve the required focus.

In particular, the element antennas 1 if located on a plane may have a variable separation, so that phasing is achieved by antenna position, instead of or in addition to variation in the relative phase of the feeding coefficients. The element antennas 1 need not be constrained to a common plane, providing a further degree of freedom. In one embodiment, the element antennas 1 may be located on a curved surface.

For equidistant element antennas 1, their separation is preferably not larger than one wavelength because of the resulting undesirable "grating lobe" appearance. The minimum distance between element antennas 1 is dictated by the element size and to avoid excessive unwanted mutual coupling. Taking these factors into account, a currently anticipated preferred separation of element antennas is approximately one wavelength.

Furthermore, the relative element antenna location and/or the relative electrical line length/phase of the feeding coefficients for the element antennas 1 need not be symmetrical about the transmission axis. In particular, the beam waist transversal position can be changed using asymmetrical phase distribution.

An antenna array 100 with a converging beam in a near field zone, i.e. having a focal plane within a distance from 3λ up to $2D^2/\lambda$ (D is array diameter, λ is the wavelength) from the element antennas 1, may include a planar microstrip array, with two layers of substrates having a common ground plane between them.

Referring to Figures 3 and 4, an example of a 4 x 4 array solution is provided. On the top layer 11 is the array of element antennas 1, see Figure 3. On the back layer 12 is the feeding network 20 including transmission lines 2, see Figure 4. Between the top layer 11 and back layer 12 is a common ground plane (not shown).

The electrical length θ to each element antenna 1 is equal to the phase ϕ determined by equation 1. Therefore, the length of the transmission lines, L can be calculated using equation 3:

$$L = \frac{\theta(\deg) \cdot \lambda_g}{360} \qquad \text{... equation 3}$$

where λ_g is wavelength on the transmission line.

The array may have a passive feeding network 20, with a planar microstrip power divider as a basic element. If an active feeding network 20 is used, with signal amplification for every element antenna 1, a high power signal may be obtained. In addition, diode phase shifters may be used for phase adjustment. With a suitable controller for the diode phase shifters, the location of the focal surface both along the transmission path and transverse to the transmission path may be varied.

There are several choices for an element antenna 1, such as dipole, rectangular or circular patch antenna, bowtie, U slotted patch and the like. If a microstrip patch antenna is used as a radiating element, the resulting array may be very narrowband, mainly due to the characteristics of the patch. However, a broadband microstrip element antenna can be used, such as a U-slotted rectangular patch with thick rigid foam as a substrate, or a slotted rectangular microstrip antenna.

Thus, the problems with energy leakage and poor efficiency are addressed by feeding the lens by the microstrip feeding network using power dividers. Efficiency may be improved as the wave does not have to pass through a dielectric lens, there may be less interference with radiation from the feeding antenna and the antenna does not require adjustment dependent on frequency. Moreover, the microstrip array focusing antenna has a compact format, small size and is very easy to use. It is a lightweight structure, with inexpensive fabrication.

The distribution of element antennas 1 in the array need not be uniform. Other distribution patterns may be used as required, including without limitation randomly distributed antenna arrays.

Where in the foregoing description, reference has been made to specific integers or components having known equivalents, then such equivalents are hereby included herein as if individually set forth.

Those skilled in the relevant arts will appreciate that modifications and improvements may be made to the invention without departing from its scope as set forth in the accompanying claims.

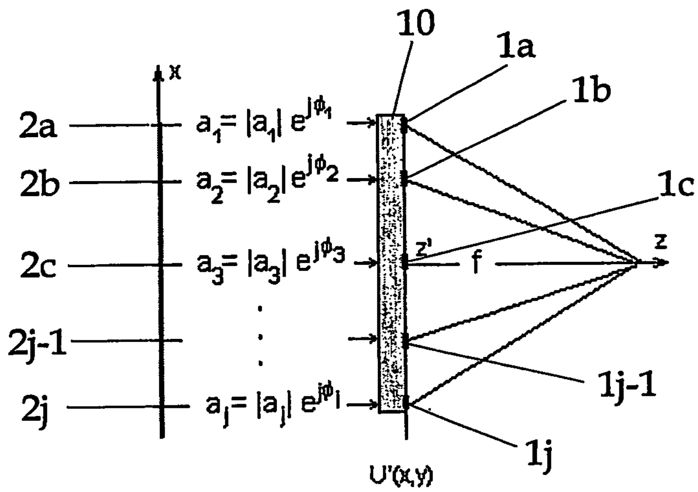

Figure 1

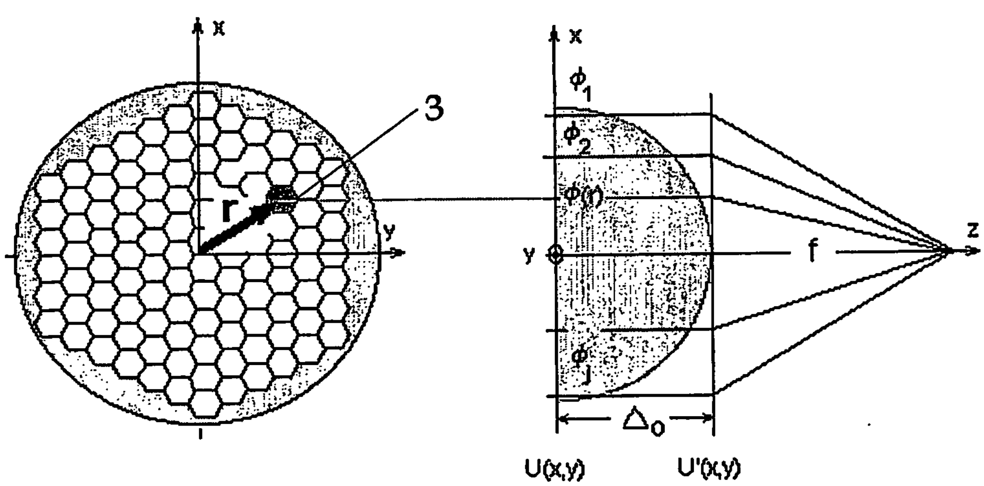

Figure 2

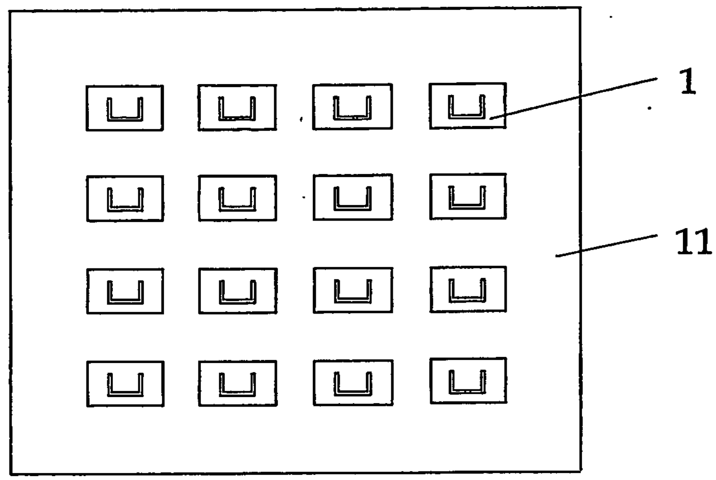

Figure 3

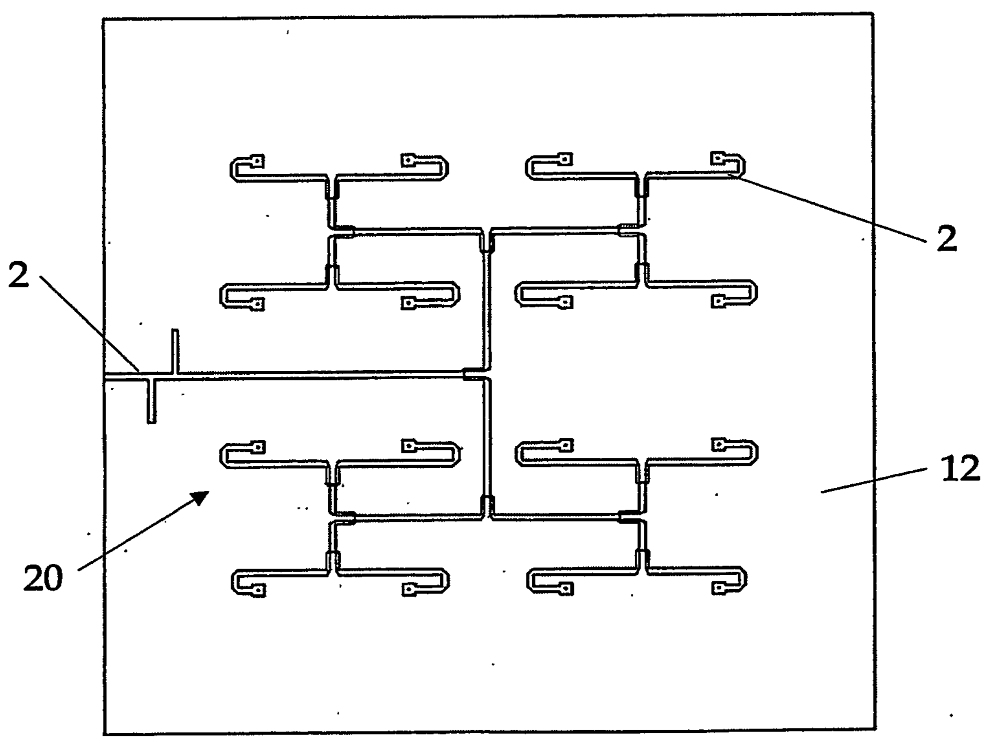

Figure 4